Status of Our Understanding and Modeling of Ignition Hohlraum X-Ray Coupling Efficiency

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Introduction

The National Ignition Facility (NIF) in the United States[1] and the Laser Megajoule (LMJ) in France[2]—the next generation of high-energy, high-power laser drivers—have the potential of achieving thermonuclear fusion in the laboratory. One key element of achieving that goal is coupling a significant fraction of that energy to a fuel capsule. We can relate the quantity of x-rays absorbed by an indirect-drive ignition capsule, E_{cap}, to the laser energy, E_L, via the expression

$$E_{cap} = \eta_{abs}\, \eta_{CE}\, \eta_{HR\text{-}cap}\, E_L \ , \tag{1}$$

where η_{abs} is the fraction of incident laser energy absorbed by the hohlraum, η_{CE} is the conversion efficiency of laser light into x rays, and $\eta_{HR\text{-}cap}$ is the fraction of generated x-rays that are actually absorbed by the capsule. As indicated in Figure 1, η_{abs} is typically assumed to be 1 – (SBS + SRS), where SBS is the fraction of incident laser light reflected or scattered out of the hohlraum by stimulated Brillouin scattering and SRS is the fraction reflected by stimulated Raman scattering.[3] E_L is nominally 1.8 MJ for both LMJ and NIF. In the case of NIF, the standard point design capsule[4,5] absorbs 150 kJ of x rays, requiring $\eta_{abs}\, \eta_{CE}\, \eta_{HR\text{-}cap}$ = 0.083. Additional constraints[4] are that the hohlraum be

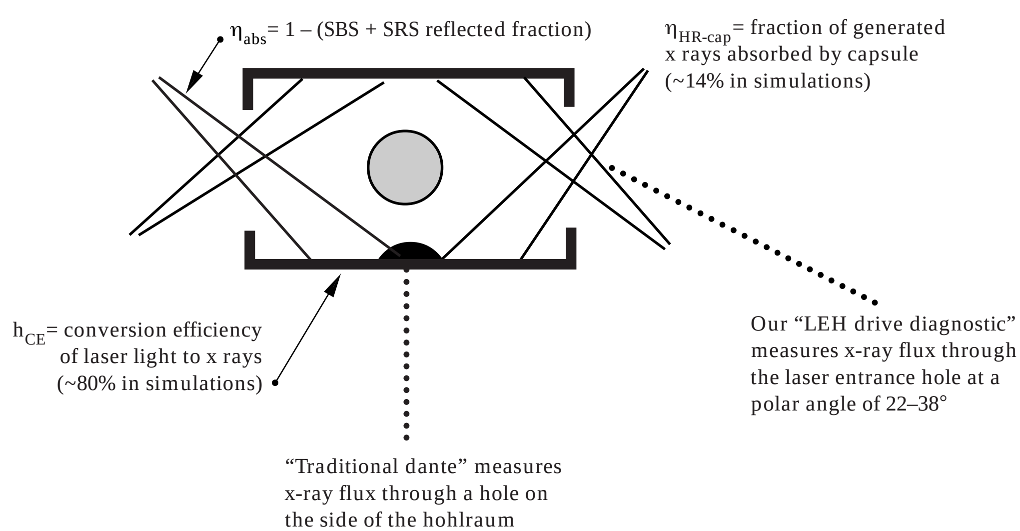

FIGURE 1. Our traditional technique for measuring hohlraum drive is to measure the absolute flux of x rays emerging through a hole in the side of the hohlraum. More recently we have changed to measuring the absolute flux of x rays emerging from the laser entrance hole (LEH) at an angle between 22 and 38°. (50-00-0199-0085pb01)

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gas filled, the laser pulse shape be carefully tailored, and the peak radiation temperature (T_r) be 300 eV.

Numerical simulations of NIF ignition hohlraums show a theoretical conversion efficiency of ~80% and an $\eta_{HR\text{-}cap}$ of ~14%, producing a theoretical $\eta_{CE}\ \eta_{HR\text{-}cap}$ of 0.11. Compared to the 0.083 required efficiency, this provides a 25% margin. This margin was intentionally incorporated into the U.S. program in the early '90s in order to compensate for uncertainties, allowing us to be off somewhat in our assumptions and still be able to achieve ignition. For example, if $\eta_{abs} = 1$ and $\eta_{CE}\ \eta_{HR\text{-}cap} = 0.11$, then $E_L = 1.35$ MJ would successfully drive our ignition design. Or if stimulated backscattering losses proved to be as much as 25% but $\eta_{CE}\ \eta_{HR\text{-}cap} = 0.11$, then NIF's expected 1.8 MJ will successfully drive the ignition design. Likewise, if $\eta_{abs} > 0.75$ and $E_L = 1.8$ MJ, then values of $\eta_{CE}\ \eta_{HR\text{-}cap} < 0.11$ would also work. Similar arguments also apply to the LMJ laser.

Given this picture of capsule coupling efficiency, much of our ongoing Nova research can be broken down into two tasks related to hohlraum energetics.

1. Make η_{abs} as close to 1 as possible in ignition hohlraums.
2. Test if $\eta_{CE}\ \eta_{HR\text{-}cap}$ is as given by hydro simulations.

Success in these two tasks will reduce the uncertainty associated with ignition and perhaps allow us to more profitably use the 25% margin built into the program.

These Nova experiments and their related analysis indicate that both LMJ and NIF coupling efficiency will meet the requirements for ignition. Ongoing experiments studying stimulated Brillouin and Raman backscattering (also known as laser plasma interactions or LPI) in ignition hohlraum "plasma emulators" imply that the total backscattered losses from these two processes should be <10%. These experiments are detailed elsewhere.[6] Here we discuss recent work examining the radiation environment of Nova hohlraums. This work indicates that x-ray production and capsule coupling indeed are very close to our modeling.

$\eta_{CE}\ \eta_{HR\text{-}cap}$

We can test our ability to properly predict $\eta_{CE}\ \eta_{HR\text{-}cap}$ by testing our ability to model/predict the relationship between a hohlraum's drive $T_r(t)^4$ and the incident laser power P_L. To see this heuristically, rewrite equation (1) as

$$\eta_{CE}\ \eta_{HR\text{-}cap}\ (\eta_{abs}\ P_L) = P_{cap} = (1 - \alpha_{cap})A_{cap}\sigma T_r^{\ 4}, \qquad (2)$$

where P_L is the laser power, $P_{cap} = d\ E_{cap}/dt$, A_{cap} is the area of the capsule, α_{cap} is the fraction of incident x rays reemitted by the capsule (also known as its albedo), and σ is the Stefan-Boltzmann constant. Thus, for a given capsule of known albedo and area, if we know η_{abs}, then a knowledge of the relationship between laser power, $\eta_{abs}P_L$, and $T_r^{\ 4}$ gives us knowledge of $\eta_{CE}\ \eta_{HR\text{-}cap}$.

For a number of years experiments have been carried out on Nova[7,8] and on other facilities[9] to measure radiation flux, or drive, in laser-heated hohlraums. The principal experimental technique was to measure absolute x-ray flux emerging from a diagnostic hole in the side of the hohlraum (which we call here "traditional dante") as shown in Figure 1. The earliest experiments demonstrated the fundamental scaling of drive with laser energy, pulse duration, and hohlraum dimensions. This work also demonstrated increasing hohlraum x-ray conversion efficiency with increased plasma filling; a consequence of the confined nature of the system.[8,9] Efforts were also made to use the traditional-dante data to test the ability of detailed numerical simulations to model the time-dependent hohlraum drive. This work was done both by U.S. researchers with the LASNEX computer code and by French scientists using the code FCI-2 (Fusion Confinement Inertial). Unfortunately, comparisons with detailed modeling often suffered at later times,[8] as shown in Figure 2. We long suspected that this disagreement was not due to fundamental errors in our two-dimensional (2D) modeling but, rather, due to the three-dimensional (3D) nature of our measurements. In particular, we suspected that a plume of cold plasma might be emerging from the hole at later times and scatter out of the diagnostic's line of sight some of the collimated x-ray flux emerging from the hole. For example, a cold plume of optical depth 0.2 could reduce the measured, collimated x-ray flux by 20%.

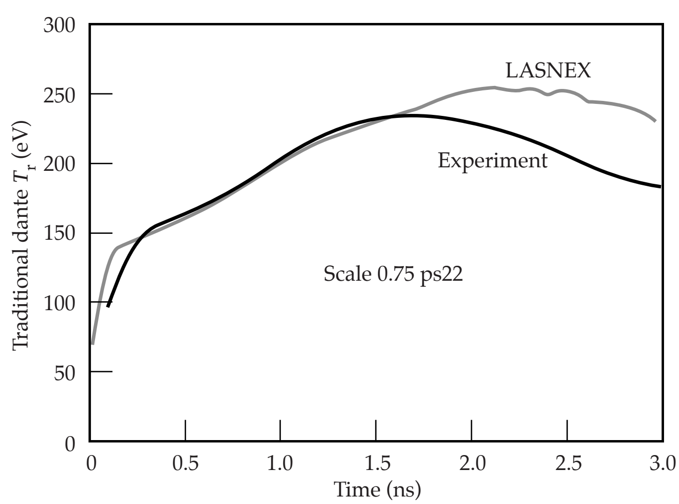

FIGURE 2. "Traditional dante" measurements of time-dependent hohlraum temperature, proportional to (x-ray flux)$^{1/4}$, agrees with detailed simulations up to a certain point. Beyond that, traditional dante is cooler than the modeling. (50-00-0199-0086pb01)

Since the publication of the papers demonstrating and explaining fundamental drive scaling,[7,8] we have redressed the issues related to detailed time-dependent drive in the course of making a number of significant changes in the way in which we study hohlraum drive. These changes include:

1. We now do indirect-drive experiments on Rochester's OMEGA facility.[10] This has demonstrated the fundamental reproducibility of radiation drive in two ways. First, results from that facility behave, quantitatively, as we expect from Nova experiments. Second, the very reproducible laser performance has resulted in drive measurements that virtually overlay one another.
2. Ten smoothed beams have been implemented on Nova,[11] greatly reducing the backscatter in many classes of hohlraums. Complementing this, we now have time-dependent measurements of stimulated Brillouin and Raman backscatter losses available on a regular basis.[12]
3. A very complementary relationship between the French ICF program and the Livermore ICF program has led to a broad range of experiments where, together, we have explored not only main-line ignition hohlraums, but also "pushed the envelope" in drive physics. Figure 3 shows a sample of the variety of hohlraums we have shot through this collaboration. They include "scale 1.0" (25-μm-thick Au cylinders 1.6 mm in diameter, ~2.4 mm long, typically with 1.2-mm-diam laser entrance holes, LEHs, in the endcaps) gas-filled and vacuum hohlraums, various-size reduced-scale hohlraums, some of which are gas filled, and very large hohlraums. These hohlraums were irradiated by a variety of pulses, including flattop pulses of varying lengths and the shaped pulses of Figure 4. As we describe below, many of these experiments have been modeled by both the French ICF code (FCI-2) as well as by LASNEX. The agreement that we find between these two independent codes and experiments is important. It increases our confidence that our successful modeling is due to having properly implemented the essential physics in both our design codes.
4. Possibly the most significant improvement we have made has been to adopt a new diagnostic line of sight; one that measures absolute x-ray flux emerging from the LEH (see Figure 1).[13,14] This was used first on OMEGA[13] and then on Nova.[14] We first tried this because of our concerns, mentioned above, that the later time discrepancy between traditional dante and 2D modeling could be due to the 3D nature of the measurement. We reasoned that a 2D code that includes all the essential physics ought to be able to model an axisymmetric line of sight, such as one through the LEH. Moreover, the plasma plume emerging from the LEH is hot (and therefore transparent to soft x rays) and can be included in our modeling.

Given this background, the balance of the paper divides into two sections. In the first section, we present a sampling of drive measurements made on the variety of OMEGA and Nova hohlraums shown in

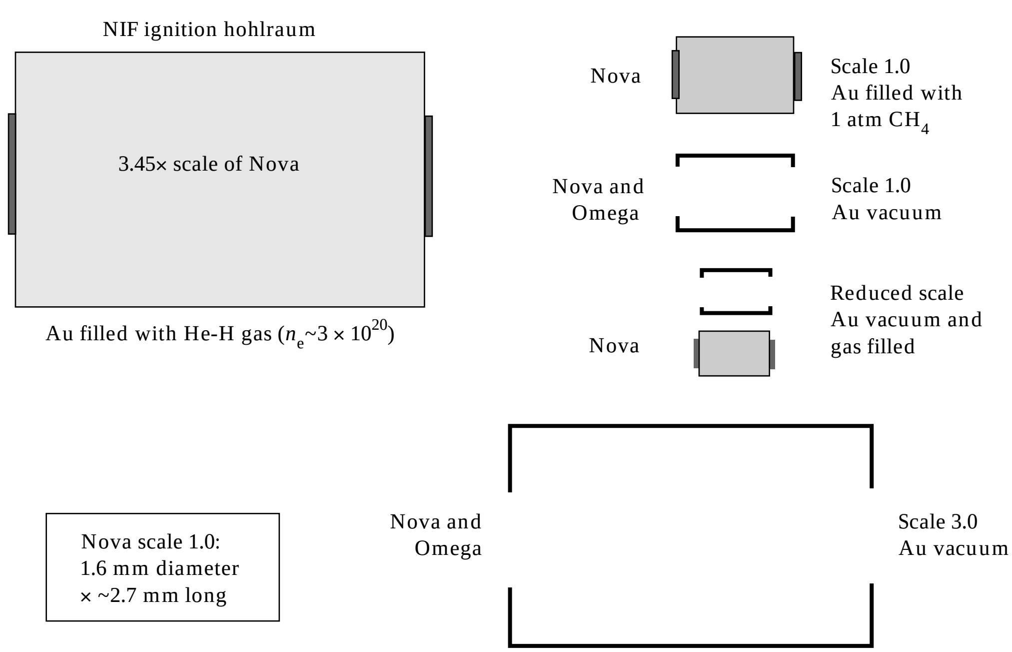

FIGURE 3. We have shot a variety of hohlraums on both Nova and OMEGA. They include gas-filled hohlraums and empty (or "vacuum") hohlraums of various sizes. A scale 1.0 Nova hohlraum is typically 1.6 mm diam, 2.5–2.8 mm long, has LEHs that are 50–75% of the hohlraum diameter, and are made of Au. Other size hohlraums are scaled from these figures. The NIF point design hohlraum is ~3.45 times the Nova hohlraum size. Gas-filled hohlraums have polyimide windows, typically 3500 Å thick. (50-00-0199-0087pb01)

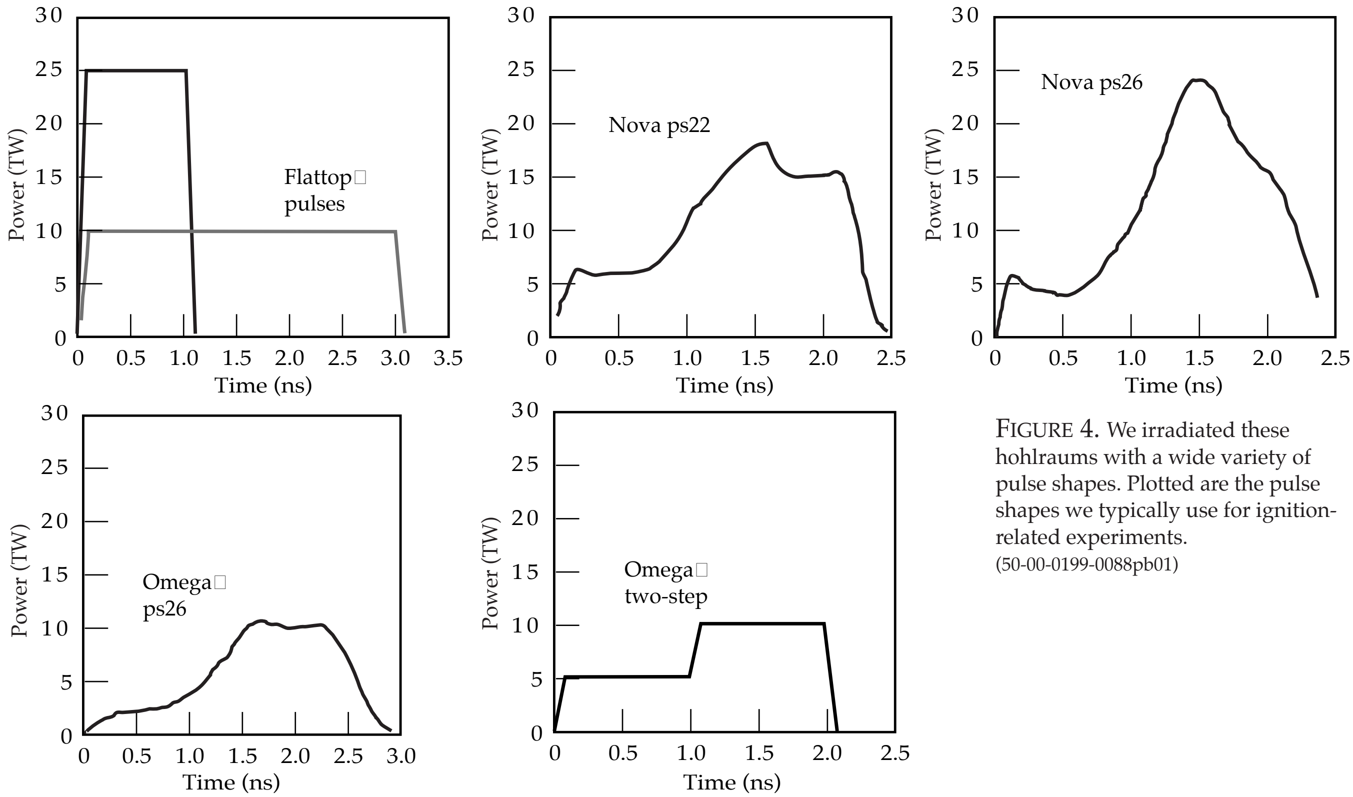

FIGURE 4. We irradiated these hohlraums with a wide variety of pulse shapes. Plotted are the pulse shapes we typically use for ignition-related experiments.
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Figure 3, heated by the range of pulse shapes (ps) discussed above. The close comparison between modeling and measurement allows us to quantify the accuracy with which we can model $T_r^4(t)$, which in turn gives us confidence that we can accurately model $\eta_{CE} \bullet \eta_{HR\text{-}cap}$ in an ignition hohlraum.

In the second section, we discuss the set of experiments that conclusively demonstrated that the late time discrepancy between traditional dante and modeling becomes progressively worse with longer pulses, while drive measured through the LEH line of sight agrees reasonably well with simulation. These experiments led to a general acceptance of the LEH line of sight and a repudiation of the traditional dante line of sight in hohlraums that “fill” with plasma. However, just because the LEH line of sight agrees with expectations, it does not mean it is right. In this section, we also discuss work we have done to independently validate this line of sight.

OMEGA and Nova Drive Measurements and Modeling

In April 1998, a series of scale 1.0 hohlraums containing capsules were fielded on OMEGA. These hohlraums were irradiated by OMEGA ps26 (see Figure 4). The hohlraums were oriented so OMEGA dante peered into the hohlraums’ LEH at a polar angle of 37.5°. The solid line of Figure 5 represents the drive measured on eight consecutive experiments which had essentially the same incident laser power vs time. Two different LASNEX simulations of the LEH drive are shown. They span the

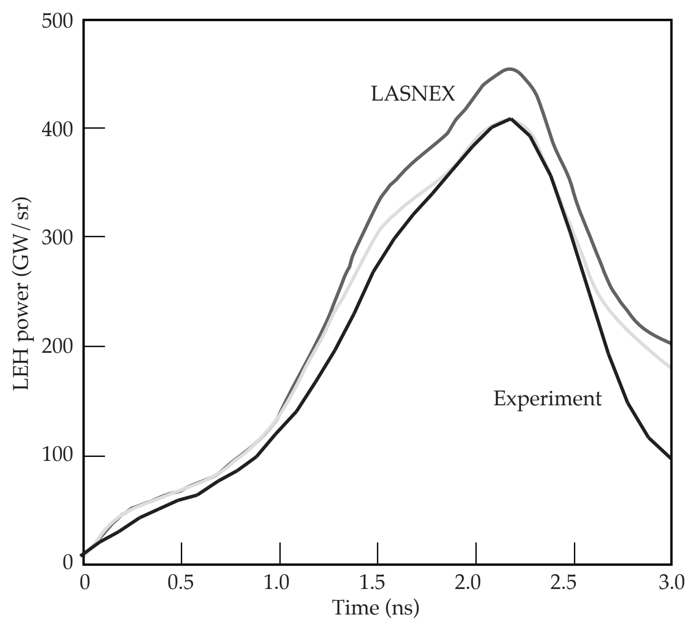

FIGURE 5. Omega ps26 drive measurment vs LASNEX. The experimental data from eight shots overlays one another.
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uncertainty in absorption. In order to model a hohlraum with either FCI-2 or LASNEX, we must first reduce the measured, incident laser power by the measured SBS and SRS losses. The upper curve of Figure 5 assumes that the backscattering losses were only what was seen coming directly back into the lens of the OMEGA beam that has a backscatter diagnostic. The lower curve, which nearly coincides with the experimental measurement, assumes that there was also an equal amount of backscatter outside the beam (where there is not yet a diagnostic). This second assumption is consistent with extensive Nova experience.[15] Regardless of the backscattering assumption, the modeling simulates the experiment within ~10% in flux not only throughout the pulse but also well after the laser is turned off, at 2.3 ns.

Figure 6 shows the drive in a methane-filled scale 1.0 Nova hohlraum irradiated by Nova ps26 (Ref. 11). All 10 of Nova's beams were smoothed with kinoform phase plates (KPP)[16] and smoothing by spectral dispersion (SSD).[17] The radiation flux emerging from the LEH at a polar angle of 25° was measured with an absolutely calibrated photo-conducting diamond (PCD)[14] "flat response" detector. Figure 6 shows detailed modeling of the LEH radiation flux made with LASNEX to be quite close to the experiment throughout the pulse; the experimental peak being about 7% higher than simulation. Similarly, Figure 7 shows a propane-filled scale 0.75 hohlraum irradiated by ps22 compared with both French and U.S. simulations. The propane fill corresponded to a fully ionized density ~1.8×10^{21} electrons/cm^3 or ~$0.2n_c$, where n_c is the critical density. The hohlraum was irradiated by 10 smoothed beams (KPP only, no SSD). The performance of this relatively high-energy-density, gas-filled

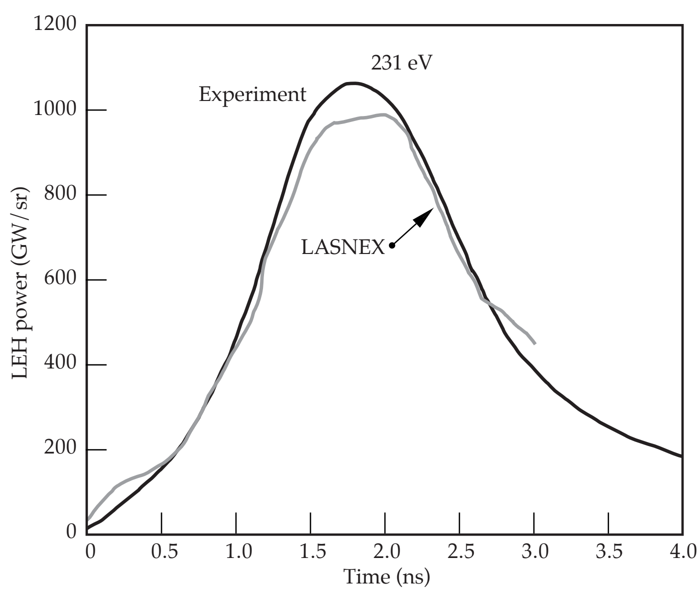

FIGURE 6. LEH drive measurement and modeling for a Nova methane-filled hohlraum irradiated by ps26. (50-00-0199-0090pb01)

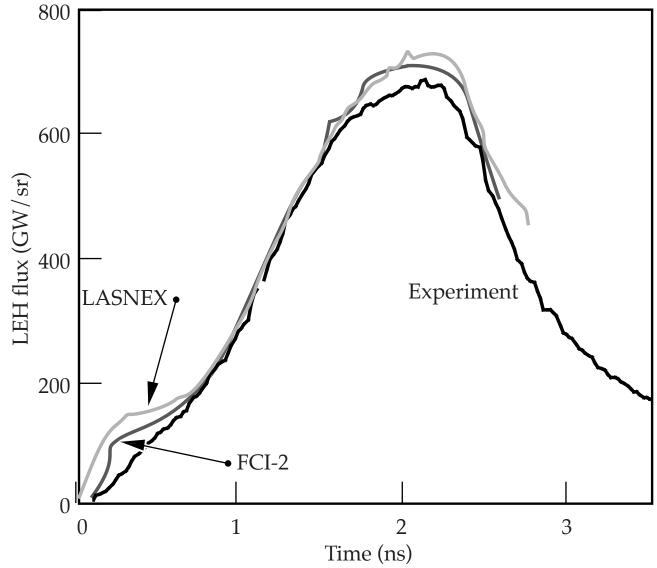

FIGURE 7. Scale 0.75 ps22 propane hohlraum. Both FCI-2 and LASNEX agree with one another and with the data. (50-00-0199-0091pb01)

hohlraum, which achieved 260 eV, is very close to both FCI-2 and LASNEX.

Finally, Figure 8 plots the LEH flux per square centimeter from three of the most extreme hohlraums we have shot. It demonstrates detailed, quantitative understanding of drive that spans two orders of

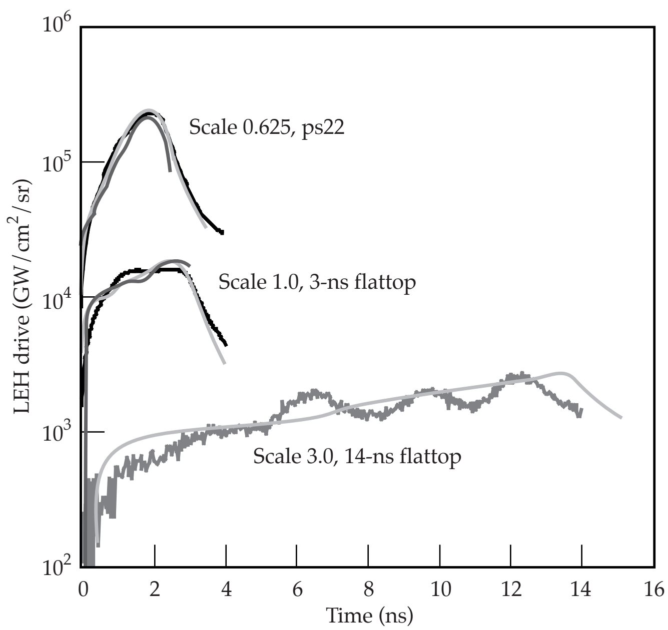

FIGURE 8. LEH measurements (GW/cm^2/sr) and modeling from three very different types of experiments. The upper curve is from a scale 0.625 hohlraum irradiated with ps22. The middle curve is a scale 1.0 hohlraum irradiated with a 3-ns flattop. The lower curve is a scale 3.0 hohlraum irradiated with a 14-ns pulse constructed by sequentially firing eight of Nova's ten beams. (50-00-0199-0092pb01)

magnitude in radiation flux/cm^2/sr. The upper curves show experiment and simulation for a scale 0.625 vacuum hohlraum irradiated by ps22. It achieved a peak T_r of ~283 eV. The middle curves plot experiment and simulation for a scale 1.0 hohlraum irradiated by a 3-ns flattop. FCI-2 and LASNEX have modeled both of these experiments and, as is shown, agree very well both with each other and with the measurements. Finally, the lower curves are the LEH drive from a scale 3.0 hohlraum irradiated by 1.9 TW for 13.5 ns. Once again there is excellent agreement between experiment and simulation. The rolling nature of the data in the lower temperature hohlraum is explained by Nova's beams being fired sequentially in order to produce this long pulse shape, instead of simultaneously.[18] This rolling cannot be included in our axisymmetric 2D modeling.

We have used LASNEX and FCI-2 to simulate, in detail, a wide variety of experiments. Examination of our entire collection of data leads us to estimate that LASNEX reproduces LEH measurements of time-dependent $T_r(t)^4$ to 4%±7%. By this we mean that the experimental $T_r(t)^4$ measurement will typically be contained within a band constructed by taking $1.04 \bullet T_{Lasnex}(t)^4 \pm 7\%$. However, the absolute calibration uncertainty of our principal x-ray flux diagnostic[19] is ±10%. Adding this in quadrature to the ±7% leads us to conclude that the true $T_r(t)^4$ will be 1.04±0.12 of LASNEX's $T_r(t)^4$.

Given this, we conclude that for a given capsule area and albedo, an ignition hohlraum's $\eta_{CE}\, \eta_{HR\text{-}cap}$ will be ~1.04±0.12 of coupling predicted by our simulations. Applying that to the NIF point design gives an estimated coupling of 0.115±0.012.

Discussion

Over the years various researchers have frequently speculated that hohlraums will begin to fail at $0.1n_c$. This has been based on the pessimistic assumption that laser plasma instabilities will necessarily wreak havoc with the intense laser beams at densities higher than this. However, pulse-shaped, reduced-scale hohlraums, such as the 0.625 scale that provided the upper radiation flux plot of Figure 8, are part of a database that belies this assumption. For example, Figure 9 plots electron density contours at 2 ns from a simulation of the scale 0.625 hohlraum. At this instant, which is the time of peak radiation drive, simulations indicate that the plasma density inside the hohlraum is everywhere greater than $0.2n_c$. Indeed, most of the plasma volume traversed by the laser would appear to be $n_c/4$ or higher. In spite of this, the hohlraum radiation flux appears to be in very good agreement with expectations indicating that the hohlraum is working well. Moreover, the measured backscattering is relatively low; the time integrated SBS + SRS being <10%.

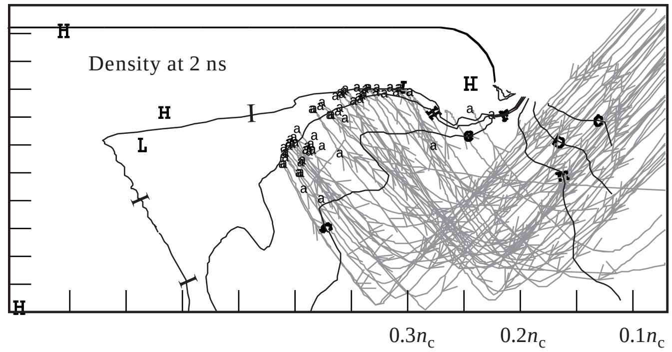

FIGURE 9. The scale 0.625 hohlraum of Figure 8 filled to relatively high plasma density by 2 ns. Nevertheless, the drive measurement indicates that it is performing as expected. (50-00-0199-0093pb01)

That hohlraums continue to operate properly, even when very filled with plasma, coupled with low backscatter losses with 10 smooth beams, has allowed us to greatly exceed performance goals set for us by the National Academy of Sciences in their Nova Technical Contract (NTC). The NTC called for temperatures >210 eV in pulse-shaped, "advanced" (e.g., gas-filled) hohlraums and >230 eV in vacuum, pulse-shaped hohlraums. Figure 10 compares predicted peak temperatures with measured peak temperatures for our database of pulse-shaped hohlraums shot from

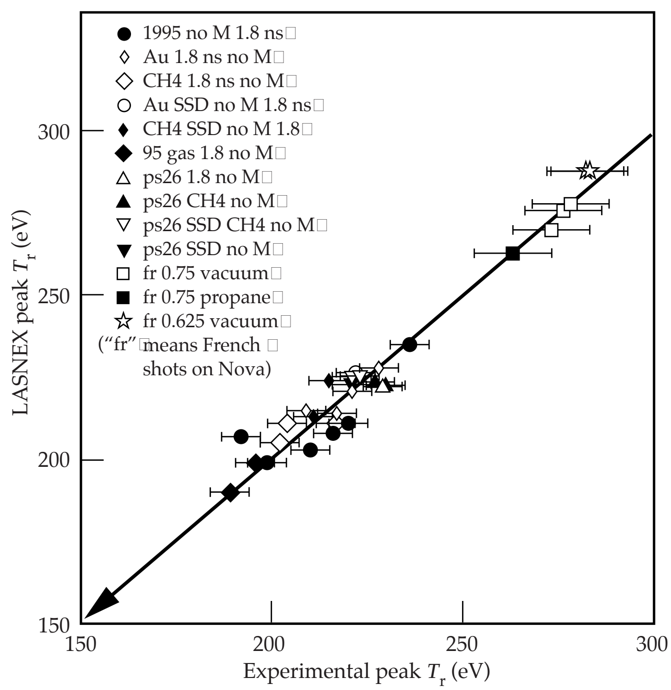

FIGURE 10. Comparisons of predicted peak temperatures with measured peak temperatures for our database of ignition-relevant pulse-shaped hohlraums shot from 1995 through 1998. (50-00-0199-0094pb01)

1995 through 1998. The NTC goals were laid out in 1990 and, at the time, were considered quite challenging. Our recent experiments very significantly exceed the NTC requirements, underscoring the technical progress we have made since that time.

The close agreement between simulation and experiment after the peak of the laser pulse provides validation of one important aspect of simulations: the way in which hohlraums manifest energy conservation at later times. In a long-pulse hohlraum, considerable thermal energy can be stored in the hot corona blowoff that fills it. After the peak of the laser pulse, this blowoff can cool, converting the released thermal energy to radiation. The later time release of stored plasma energy is a noticeable part of Nova-scale energetics and an even more important part of larger scale ignition hohlraum energetics. Without it, significantly more late-time laser power would be needed to maintain the desired radiation temperature.[8,9]

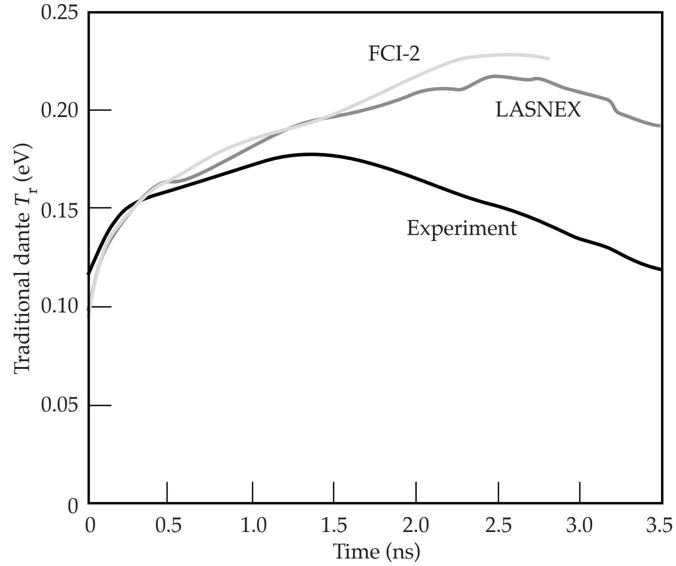

FIGURE 11. Traditional dante measurement of radiation temperature from a 3-ns BAP experiment compared with modeling. (50-00-0199-0095pb01)

Validating the LEH Line of Sight

In 1997 we performed a compelling series of experiments which demonstrated that in situations where there is gross disagreement between traditional dante and modeling, the LEH line of sight indicates that the hohlraum is in fact performing as expected. This sequence of experiments provided the strongest evidence to date that there is something wrong with the traditional dante line of sight later in times, when the hohlraums fill with plasma (more precisely, after the time at which wall blowoff stagnates on axis, thereby ending the hohlraum's free-expansion phase). This "build-a-pulse" (BAP) experimental series consisted of scale 1.0 vacuum hohlraums with 75% LEHs irradiated with flattop laser pulses that varied from 0.6 ns to 3 ns. The dante holes themselves were the standard "Be-washer" type.[7] For example, Figure 11 plots the observed and simulated traditional dante flux vs time for a hohlraum irradiated by a 3-ns flattop. It is quite evident that after ~1 ns, there can be extraordinary disagreements between this measurement and modeling with both codes. For very filled systems like this, the disagreement can be far worse than we typically saw (cf Figure 2). In this case there is approximately a factor of three difference in integrated flux. In contrast, the drive measurements made through the LEH on all these experiments (e.g., the middle curves of Figure 8 show the 3-ns BAP experiment and modeling) were very much closer to our expectations throughout the pulse and even after the pulse.

The gross difference between findings from the two views quickly led to the LEH line of sight becoming the preferred drive diagnostic for virtually all experiments. However, we were quite concerned that just because the results are close to our expectations, it does not guarantee that they are right. For example, one could construct a pathological situation that could make the LEH drive seem "right" yet still starve the center of the hohlraum of radiation. This scenario combines lower than expected radiation production with greater than predicted plasma evolution. This could conspire to move the weaker source close to the LEH, where it would look bright but no longer effectively heat the center of the hohlraum.

In an effort to validate that the central temperature in a hohlraum really is close to modeling, we performed two types of experiments. The first type was to measure the burn-through time of thin gold foils covering holes in the center of a hohlraum. The thicknesses were chosen so that the burn-through times would readily distinguish which of two grossly different drives was more likely correct. These burn-through measurements were part of our second series of BAP experiments. We observed burn-through signals on four of six foils placed on the hohlraums (no signals were seen on two foils which were thick and should have been weak). The burn-through times of the four foils is consistent with simulated drive (which, for these hohlraums, is very close to the simulated LEH drive). Figure 12 plots expected burn-through time against observed burn-through time. The expected times were calculated by a 1D LASNEX simulation using STA opacities.[20] The simulated foils were driven with multifrequency radiation sources extracted from LASNEX simulations of each experiment. The close agreement between observed burn-through time and simulated burn-through time is further evidence that hohlraums, at late-time, are performing approximately as modeled. This, in turn, is evidence that the LEH

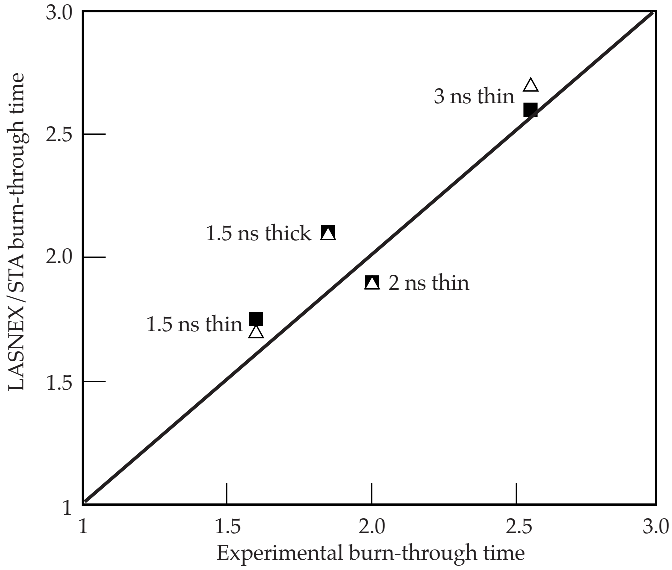

FIGURE 12. Burn-through foil measurements made on BAP hohlraums are consistent with drive measurements made through the LEH and with simulation. (50-00-0199-0096pb01)

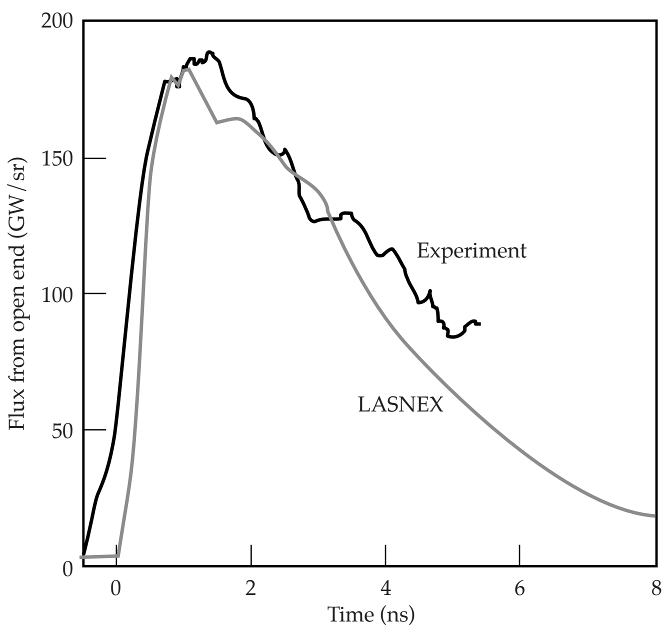

FIGURE 13. Radiation flux emerging from the midplane of a half-hohlraum irradiated by a very long pulse. This indicates that a real hohlraum midplane will not see a radiation flux that is significantly different than that expected from radiation hydrodynamic simulations. (50-00-0199-0097pb01)

line-of-sight provides a valid measure of late-time drive while the traditional-dante line of sight may not.

Complementing the burn-through measurements, we also have made a few measurements on "half-hohlraums." The basic idea is to cut a hohlraum in half, irradiate it through only one end and use the "LEH" drive diagnostic to measure the x-ray emission through the open, unirradiated end. If the open end of the hohlraum were, in fact, being starved of radiation at later times, then it should be very evident in the LEH drive diagnostic. Figure 13 is a comparison of simulated and measured radiation flux vs time from a scale 1.41 hohlraum irradiated by an 8-ns-long drooping pulse. In the simulated hohlraum, there is a large amount of plasma evolution that progressively moves the laser deposition region closer to the LEH throughout the pulse. Nevertheless, the flux exiting the midplane of this half-hohlraum is quite close to what we expect, indicating that in this very long-pulse system the center of the hohlraum is not "starved" of radiation but is, in fact, receiving close to the expected amount.

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